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ACTIVE GUIDED-WAVE DEVICES.(U)

1979 A B BUCKMAN N00014-75-C-0753

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Final Report, Office of Naval Research Contract N00014-75-C-0753
NR371-007: Active guided-wave devices.

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INTRODUCTION

The overall purpose of this contract was the theoretical and experimental study of multilayer guided-wave optical structures, and the search for novel effects introduced by the stratification, which might be exploited to create active guided-wave devices with performance characteristics superior to their one-layer counterparts. This final report summarizes the principal research accomplishments under the contract, and concludes with some recommendations concerning future directions of research on multilayer guided-wave optics.

PRINCIPAL ACCOMPLISHMENTS

A. General theoretical framework:

We recast existing matrix formalism developed for multilayer reflecting structures into a form which allowed for evanescent as well as propagating waves normal to the interfaces.[1] The result is a compact expression allowing direct determination of the modal equation for a planar dielectric stratified waveguide structure. This treatment allows one to visualize a ray-optic model of guided wave propagation within the structure, but is exactly equivalent to an

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analysis using the wave equation and appropriate electromagnetic boundary conditions. From the modal equation thus obtained, the effect of a small change in any of the parameters (refractive indices or layer thicknesses) on the effective refractive index (indices) of the guided mode(s) can be calculated.

Although it was not attempted under the contract, this calculation can easily be modified to include the effects of optical gain or loss in one or more of the layers. Therefore, it is well suited for analysis of guided waves in stratified hetero-junction structures such as those fabricated in $Ga_xAl_{1-x}As$.

B. Applications:

Three-layer[1] and five-layer[2] structures in which the refractive index of one of the media is varied by means of the electrooptic effect were studied, using the analysis described above. With properly chosen refractive indices and thicknesses, substantial improvements in performance over single-layer structures, measured in terms of the effective electrooptic coefficient,[1] are predicted. In both cases studied, refractive index and thickness in each layer must be very closely controlled, if the structure is to perform as designed, since the effective electrooptic coefficient is a sharply peaked function of these parameters. Since the thicknesses in the theory scale as thickness ÷ wavelength, sharply peaked wavelength dependence is to be expected as well.

Since in the mm- and sub-mm wavelength regions free-carrier contributions to refractive index are significant, we employed this

analysis to study an electronic phase-shifter with a stratified semiconductor waveguide structure.[3] The active region of this structure is the intrinsic region of a p-i-n diode. Since the theory is independent of the mechanism used to perturb the refractive index, it is not unexpected that stratified devices can be designed which exhibit greater phase-shifts per unit length than their single-layer counterparts. In addition, for injection-driven devices, required drive power can be minimized by designing the structure with the intrinsic region as thin as practical.

The three-layer device[1] can be made to act as a planar low-pass or high-pass filter by forming respectively a ridge or a groove in the low-index middle layer. In either case, there is a well defined cutoff frequency beyond which the wavelengths retained by the filter are guided along the ridge or groove, while those rejected by the filter leak away in directions parallel to the interfaces. Experiments to confirm these predictions were nearing completion in August 1980, and the results will be submitted for publication.[4]

Since any electrooptic device will include electrodes somewhere in the system, we also studied metallic layers in the context of stratified waveguiding structures. We found that the lossy, high effective index TM modes, reported by many other workers on structures containing negative permittivity metallic regions, can have propagation constants that are strong functions of the thickness of the metal layer. This occurs when the metal layer is thin enough to allow coupling in the interior between the surface plasmon modes

at the surfaces.[5] The change in the propagation constant was observed experimentally as a shift of the minimum in TM-reflectance vs. angle of incidence. Results were in good agreement with the predictions of the propagation constants for a two-layer structure with one negative permittivity layer obtained from the multilayer waveguide theory.[1]

For accurate comparisons of theory and experiments on multilayer guided wave structures, it is important to characterize the dielectric multilayer structure independent of any measurements involving waveguiding. Two approaches were developed in the course of this work. For evaporated or sputtered films we developed a simple one-step approach to simultaneously determimining the film refractive index and thickness with a commercially available Fizeau interferometer.[6] Measurement precision is to within ~30Å for thickness and ~.01 for refractive index, for transparent films in visible light. Small non-zero optical absorption in the film has a negligible effect on index and thickness measurements. For layers formed by indiffusion or polishing, multiple angle-of-incidence ellipsometry provides the capability of determining a refractive index profile. This method was used to characterize waveguiding layers of $LiNb_xTa_{1-x}O_3$ formed by diffusion of Nb into $LiTaO_3$. The surprising result was the detection of a waveguiding layer in the "bare" $LiTaO_3$ samples which apparently forms during surface polishing.[7] Our measurements show that this high-index layer is annealed away at temperatures substantially less than the Curie temperature for $LiTaO_3$ or the temperatures

normally used for Nb indiffusions.

Our attempts to construct and operate a three-layer active device with one electrooptic layer have not been successful as of this date, for reasons which are not clearly understood. The devices, designed according to Ref. 1 and operated as beam deflectors for guided waves, *do not exhibit* the predicted modulation enhancement. The electrooptic layer ($LiNb_xTa_{1-x}O_3$ on $LiTaO_3$) really has a Gaussian index profile instead of the step profile analyzed in Ref. 1. It may be that this graded index variation in the active region does not produce more mode index variation than a single layer electrooptic structure.

CONCLUSIONS AND RECOMMENDATIONS

This study has laid the foundation for the exploitation of stratified structures in guided wave optics. Proper choice of indices and thicknesses yield structures with enhanced sensitivity to wavelength, mode, or refractive index, as compared with single-layer waveguide structures.

The experimental part of this research would have been enhanced if a very precise, highly repeatable method of film formation had been used to fabricate devices. Molecular beam epitaxy with the $Ga_xAl_{1-x}As$ material system could have provided this precision in a medium with an appreciable electrooptic effect.

Novel and useful effects may be present in layered waveguide structures where one or more layers have optical gain. This

possibility should be investigated in future work.

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